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INVESTIGATION OF THE COEFFICIENT OF FRICTION OF VARIOUS GREASES AND DRY FILM LUBRICANTS AT ULTRA HIGH LOADS FOR THE SATURN HOLD DOWN ARMS

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ABSTRACT

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A series of high load, low speed sliding friction tests was made on 8 fluid lubricants and 18 dry lubricants at normal unit loads from 10,000 psi to 150,000 psi. Four different substrate materials having a range of hardnesses from Rockwell C 18 to Rockwell C 55 were used. The ultimate load capability of both fluids and dry films is a function of substrate hardness with the best ultimate load capability being provided by inorganically bonded molybdenum disulfide films with small amounts of graphite added. The coefficient of friction of the fluid lubricants appears to be an inverse function of substrate hardness and a direct function of the normal load. The coefficient of friction of the dry lubricants is an inverse function of the normal load, but it does not appear to be related to the substrate hardness.

Author

LIST OF TABLES

Table	Title	Page
I	Maximum and Minimum Coefficients of Friction of Various Greases vs Normal Unit Load	11
II	Maximum and Minimum Coefficients of Friction of Various Dry Film Lubricants vs Normal Unit Load	12

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Test Equipment	14
2	Schematic of High Load Tester	15
3	Friction Measurement Recording	16
4	Greases, Ultimate Load Capabilities with Four Substrate Materials	17
5	Greases, Coefficient of Friction vs Unit Load for Seven Lubricants, Substrate 440C Rockwell C 52-55	18
6	Coefficient of Friction vs Unit Load Grease G-1 with Four Slider and Substrate Materials	19
7	Galling on 440C Steel Test Plate Lubricated with Grease G-1	20
8	Dry Lubricants, Ultimate Load Capability for Four Lubricant Classes, Substrate Material 440C Steel	21-22
9	Four Classes of Dry Lubricants, Coefficient of Friction vs Unit Load Substrate 440C Rockwell C 52-55	23-24

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	1
TEST EQUIPMENT	2
DISCUSSION AND RESULTS	4
CONCLUSIONS	9
REFERENCES	10

LIST OF ILLUSTRATIONS

(Concluded)

Figure	Title	Page
10	Test Plates	25
11	Dry Films, Ultimate Load Capability vs Substrate Hardness	26
12	Dry Films, Average Coefficient of Friction vs Substrate Hardness at 10,000 psi and 30,000 psi	27

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SUMMARY

A series of high-load, low-speed sliding friction tests was made in connection with the development and testing of lubricants for the Saturn V test stand vehicle supports and hold down arms. Twenty-six different lubricants were tested on four different base steels through a series of unit loads from 10,000 to 150,000 psi (based on projected area). Several dry film lubricants provided acceptable coefficients of friction and wear lives on hardened (Rockwell C 55) stainless steel; however, the lowest coefficient of friction (0.106 to 0.025) was obtained with a lubricant that is designated MLF-9. This lubricant is a mixture of molybdenum disulfide, graphite, and bismuth in a binder of aluminum phosphate. In general, it was concluded that the molybdenum disulfide based dry film lubricants in inorganic binders are suitable for use at unit loads up to 150,000 psi and slow sliding speeds when they are applied to substrates with sufficient hardness to prevent surface deformation in the applicable load range.

INTRODUCTION

A summary of the various lubrication problems which have been encountered in both ground support systems and space vehicles during the past few years indicates that many problems concern heavily loaded, low speed, sliding surfaces. Engine gimbal bearings represent one type of bearing problem which falls into this category and which has been discussed elsewhere (ref. 1 and 2). Another problem in this category, the subject of this paper, involves the clamps on hold down arms of test towers and launch pedestals. The launching procedure for Saturn vehicles includes a hold down time until full thrust combustion stability of the booster stage engines is verified. Hold down clamps are put in place while the vehicle is erected and are released at lift-off. Therefore, the clamps must provide for sliding lateral motion due to

thermal expansion and wind loading during launch preparations. A laboratory device was designed and built to simulate movement of the booster on the hold down supports for economical evaluation and selection of materials. The simulator is capable of providing unit loads up to 150,000 psi on projected areas of 0.59 square inch. A total of 26 lubricants was evaluated on four different base materials. Although all of these evaluations were made under earth ambient conditions, the lubricants which provide the highest load carrying capabilities also appear to be suitable for vacuum and for high and low temperature operation (ref. 3).

TEST EQUIPMENT

A photograph of the test device is shown in FIG 1, and a schematic of the device is shown in FIG 2. The test device consists of a frame on which is mounted a 50-ton mechanical jack. The jack applies a normal load to the test specimens through a 100,000-pound load cell. The test specimens consist of two self-aligning plates which fit into machined recesses in the frame and load cell support plate. A slider is positioned between the self-aligning plates and is connected through a load cell to a gear-motor driven mechanical jack. The normal load is measured by a strain indicator, and the friction load is recorded on a fast response oscillograph.

The following parameters were maintained during the lubricant evaluation:

1. Load Range - 10,000 to 150,000 psi in 10,000 psi increments

2. Sliding Speed - 0.67 inch/minute

3. Sliding Distance - 1/2 inch in each direction for a total of a 5-inch linearly reciprocating motion at each load

4. Specimen Finish - 28 to 32 RMS

5. Specimen Projected Contact Areas - 0.59 square inch. However, projected areas of up to one square inch were used to cross-check friction and load-carrying capabilities of several lubricants.

6. Specimen Substrate Materials and Hardnesses

    a. 440C Steel, Rockwell C 52 to 55

    b. 4340 Steel, Rockwell C 43 to 45

    c. 17 - 7 PH Steel, Rockwell C 39 to 40

    d. HY80 Steel, Rockwell C 18 to 20

7. Test Repetition - All tests were repeated, and, if materials were available, additional repetitive tests were made.

8. Lubricant Application - Dry and solid lubricants were applied either by the manufacturer or by personnel of the Materials Division, Propulsion and Vehicle Engineering Laboratory, at the Marshall Space Flight Center, following the manufacturer's instructions.

TEST PROCEDURE

All lubricants were applied to the top and bottom test plates, and the slider was unlubricated. The test specimens were mounted in the test device and loaded to 10,000 psi. The drive motor was started, and the slider was driven 1/4 inch from center. At this point, the slider direction was reversed, and the slider was moved to 1/4 inch past center in the opposite direction. This reciprocating motion was continued until a total of five inches of sliding had taken place. The unit normal load was then increased to 20,000 psi and the procedure repeated. The normal load was increased in 10,000 psi increments for each test to a maximum of 150,000 psi or until the lubricant failed. FIG 3 shows a recording of the friction force encountered during sliding. The friction coefficient calculations were based on the maximum values recorded during each 1/2 inch of travel, excluding the peaks caused by static friction. The average coefficient of friction was obtained by averaging the ten values obtained during operation at one unit load. Lubricant breakdown or the ultimate load capability was indicated by rapidly increasing friction.

DISCUSSION AND RESULTS

Testing - Fluid Lubricants

The following fluid and fluid-powder mixtures were tested to failure in the high load tester:

1. Commercial G-1 - halogenated chlorofluorocarbon grease with 5% MoS_2 powder added (Halocarbon Grease X-25-10M-5A)

2. Commercial G-2 - halogenated chlorofluorocarbon grease (Halocarbon Grease X-25-10M-5A)

3. Commercial G-3 - fluorosilicone grease (Dow Corning XG-5-0034)

4. Commercial G-4 - fluorocarbon grease with a Teflon filler (Dixon 95-1)

5. Commercial G-5 - hydrocarbon based grease with extreme pressure (E. P.) additives (Lubriplate)

6. Commercial G-6 - hydrocarbon based grease with E. P. additives according to MIL-G-7118 (Shell)

7. Commercial G-7 - chlorofluorocarbon grease with Teflon powder added (Liquid-O-Ring)

8. Commercial G-8 - mixture of MoS_2 and a hydrocarbon oil (Molykote G)

In this series, all of the lubricants were tested on 440C steel, and a sampling was made by using other substrate materials.

Ultimate load capability.- As shown in FIG. 4, lubricant G-8 provided the best ultimate load capability of all the fluids tested on a hard substrate. Since G-8 contains over 50% molybdenum disulfide powder, it is questionable if it can be considered a true fluid. Also, lubricants G-1 and G-2 provided excellent load carrying capabilities

on hard steel substrates.

Coefficient of friction.- The coefficient of friction of all the fluids except those containing molybdenum disulfide powder, such as G-1 and G-8, increased with increasing load, as shown on FIG 5. The data in FIG 5 were obtained on a substrate material having a hardness of Rockwell C 52 to 55. The maximum and minimum coefficients of friction for all tests on fluids are shown in Table I. The extreme values shown in this table are the maximum and minimum values achieved during several repetitive tests of a lubricant instead of the average values as shown in FIG 5 and 6.

Effect of substrate material.- Figure 6 illustrates the effect of the substrate material on the coefficient of friction and the ultimate load capability of the lubricant G-1. The increase in load-carrying capability and the decrease in coefficient of friction with increasing substrate hardness are evident in these data.

Failure.- Fluid lubricant breakdown generally was noted by a sharp increase in friction force caused by galling of the substrate surface, as shown in FIG 7. The substrate surfaces were destroyed quickly after the ultimate load capability of the lubricant was reached.

Testing - Dry Films and Solid Lubricants

All dry film or solid lubricant tests were made by using 440C steel substrates and slider materials, and sampling was made with other substrate and slider materials to provide data on the effect of various substrate hardnesses. The following is a list of the dry or solid lubricants tested during this program:

1. Zirconium Silicate, flame sprayed and ground with MoS_2 burnished into the surface

2. Chromium Oxide, flame sprayed and ground with MoS_2 burnished into the surface

3. Aluminum Oxide, flame sprayed and ground with MoS_2 burnished into the surface

4. Commercial D-1 - Teflon-fiber glass fabric with a resin binder (Fabroid I)

5. Commercial D-2 - Teflon-fiber glass fabric with a special organic binder (Fabroid G)

6. MLF-5[1] - mixture of MoS_2, graphite, and gold powder in a sodium silicate binder

7. Commercial D-3 - mixture of MoS_2 and graphite in a sodium silicate binder (Molykote X-15)

8. MLF-8[2] - mixture of MoS_2, graphite, and gold powder in a binder of aluminum phosphate

9. MLF-9[3] - mixture of MoS_2, graphite, and bismuth powder in an aluminum phosphate binder

10. Commercial D-4 - proprietary process for applying MoS_2 insitu by electroplating molybdenum and forming molybdenum disulfide with an H_2S treatment (Molykote 321-X)

11. Commercial D-5 - air drying resin bonded MoS_2, graphite lubricant applied from a spray can (Lubribond A)

12. Commercial D-6 - oven cured MoS_2 lubricant with a phenolic binder (Electrofilm 4306)

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1 - Dry film lubricant developed by Midwest Research Institute under Contract NAS8-1540.

2 - Ibid

3 - Ibid

13. Commercial D-7 - silicon resin bonded MoS_2 lubricant (Electrofilm 2007)

14. Commercial D-8 - proprietary film containing MoS_2 and graphite in an inorganic, zinc based binder (Lubco 905)

15. Commercial D-9 - unbonded "leaded" graphite film applied by a proprietary process (Microseal)

16. Commercial D-10 - 50% by weight graphite and 50% by weight MoS_2 lubricant bonded with a high temperature silicone phenolic resin (Electrofilm 2006)

17. Commercial D-11 - inorganically bonded dry film lubricant containing MoS_2 and graphite (Drylube 805)

18. Commercial D-12 - thermosetting film of MoS_2 and 10% graphite in an "elasticized" phenolic binder (Electrofilm 4396)

Ultimate load capability - Figure 8 shows the ultimate load carrying capabilities which were determined during all tests using substrates and sliders of 440C steel. The lubricants in FIG 8 are divided into four classes: Unbonded, Resin Bonded, Inorganically Bonded, and Special. The ultimate load carrying capability of the inorganically bonded dry films generally is much greater than that of any other class of lubricants with the exception of the inorganically bonded film D-11, which failed at 20,000 to 30,000 psi. It is of interest to note that this same film, D-11, has provided exceptional wear life during light load, high speed sliding tests as reported by other investigators (ref. 4). Several investigators (ref. 5) have reported very good load-carrying capabilities with the special lubricants D-1 and D-2; however, with the slider configuration used in these tests, the lubricants were subject to shearing by the slider edge and failed from a planing effect. The load-carrying capability of the unbonded films was not expected to be high because of the extremely thin films applied in these processes. Of this group, only lubricant D-4 showed even fair load-carrying capabilities. The results of the tests on the resin bonded films were disappointing since all specimens galled below 150,000 psi. Only two of the lubricants, D-7 and D-12, reached the 100,000 psi range. In comparison, lubricants MLF-5, MLF-9, and D-8 in the inorganically bonded group supported loads to the maximum capacity of the test device, and lubricant D-3 operated consistently in the 100,000 psi range.

Coefficient of friction.- Figure 9 provides a comparison of the coefficient of friction through the total load range of the various dry lubricants applied to 440C test specimens. In the unbonded films, D-9 provided an exceptionally low friction coefficient in the range of about 0.02 to 0.03 up to 30,000 psi. The resin bonded lubricants provided coefficients of friction from about 0.20 to about 0.07 with increasing load. The high coefficient of friction exhibited by lubricants D-6 and D-11 probably indicated that a small amount of film breakdown occurred at the lowest loads. The inorganically bonded films provided the lowest coefficient of friction at high loads. Three of these lubricants maintained a continuous supporting film at unit loads up to 150,000 psi. Each of these films had coefficients of friction in the range of 0.04 to 0.07 from 30,000 psi to 150,000 psi.

A photograph of one of the test specimens which was operated successfully to 150,000 psi is shown in FIG 10, along with a specimen which failed at 110,000 psi. The original film on the unfailed specimen was approximately 0.0005 inch to 0.0007 inch thick; whereas, the film on the wear track shown in FIG 10 is approximately 0.0001 to 0.00015 inch thick. However, 0.0001 inch appears to be a minimum film thickness on the wear track since tests of up to 250 inches travel at 100,000 psi failed to produce a thinner film.

Effect of substrate materials.- The effect of substrate hardness on ultimate load capability for dry lubricants is illustrated in FIG 11. Only a few selected lubricants were tested sufficiently on various substrate materials to be included on this plot; however, spot checks made on other lubricants indicate that the trend shown in FIG 11 generally is applicable to all of the lubricants tested. If several tests were made on the same lubricants and substrate material, an average of the ultimate load-carrying capability is shown. The increase in ultimate load capability with increasing substrate hardness was expected.

A decrease in the coefficient of friction with increasing substrate hardness was expected for the dry film lubricants. As shown in FIG 12, however, no set pattern seems to exist that relates substrate material to coefficient of friction with the dry film lubricants. At 10,000 psi unit load, lubricant D-3 showed a decrease in coefficient of friction with increasing substrate hardness while MLF-5 and MLF-9 maintained constant or slightly increasing coefficients of friction with increasing substrate hardness. At 30,000 psi, the pattern remains the same. No explanation is known for the difference in response of

the MLF-5 and D-3 lubricants since they are similar except for the addition of a metallic powder to the MLF-5. It appears that within the ultimate load limit of the lubricant-substrate combination that the coefficient of friction does not vary dramatically with substrate hardness at high loads.

Table II shows the maximum and minimum coefficients of friction which were obtained for all tests of dry film lubricants on various substrate materials. The data shown for each lubricant give the extremes in coefficient of friction which were obtained through a number of repetitive tests.

CONCLUSIONS

1. Ultimate lubricant load capabilities of 150,000 psi and above can be achieved with inorganically bonded MoS_2 graphite films applied to hardened (Rockwell C 42-55) substrates. The addition of a small amount of graphite to molybdenum disulfide films increases the ultimate load carrying capabilities of both resin and inorganically bonded films.

2. The resin bonded dry films failed at lower unit loads than the inorganically bonded films.

3. The unbonded dry lubricant films are not suitable for high load operation above 50,000 psi.

4. Both the resin bonded and the inorganically bonded dry lubricants exhibited decreasing coefficients of friction with increasing normal load. The coefficient of friction varied from 0.12 to 0.025 at normal unit loads from 10,000 psi to 150,000 psi, respectively.

5. Of the fluid lubricants tested, a halogenated fluorocarbon provided the best ultimate load capability of approximately 90,000 to 100,000 psi on a 440C steel substrate.

6. The coefficient of friction of fluid lubricants generally increased with increasing normal unit load.

7. At high loads, the coefficient of friction of the fluid lubricants tends to decrease with increasing substrate hardness. No definite pattern that relates the coefficient of friction to substrate hardness for the dry film lubricants seems to exist.

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3. Hopkins, Vern; and Gaddis, D. H.: Research on Bearing Lubricants for Use in High Vacuum. Annual Summary Report for Contract NAS8-1540, Midwest Research Institute, March 23, 1962 - April 22, 1963 and April 23, 1963 - May 22, 1964.

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TABLE I. - MAXIMUM AND MINIMUM COEFFICIENTS OF FRICTION OF VARIOUS GREASES VS NORMAL UNIT LOAD

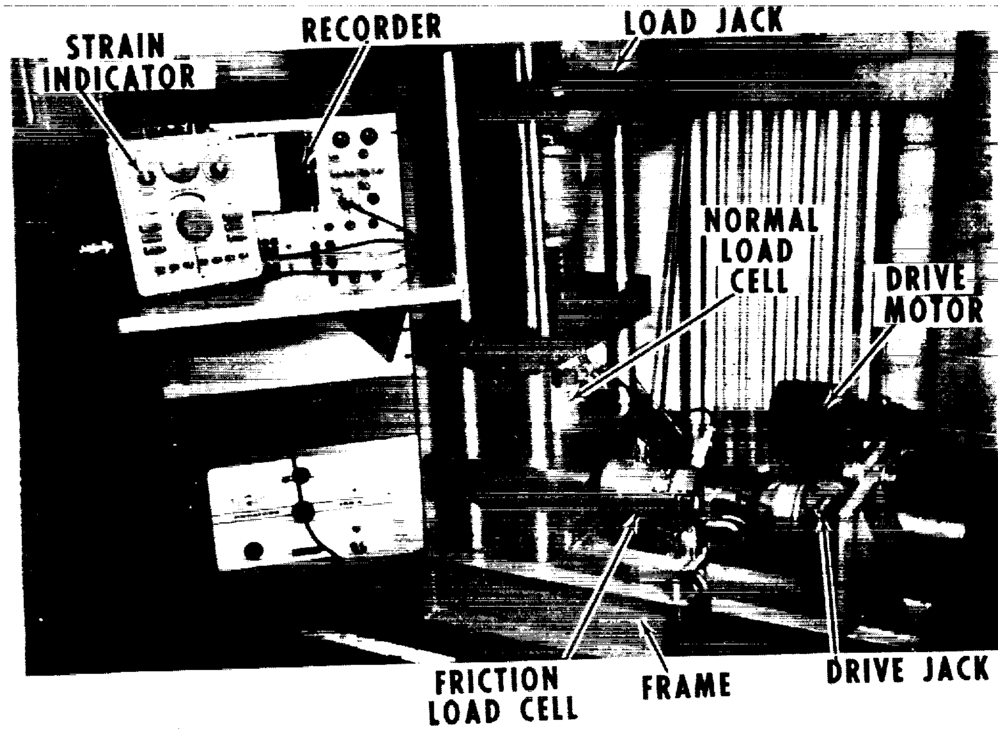
		NORMAL UNIT LOAD KSI														
BASE MAT'L	LUB.	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
440C	G8	.096 .137	.089 .089	.077 .083	.074 .077	.071 .074	.073 .078	.074 .075	.072 .073	.071 .072	.068 .074	.066 .071	.065 .069	.063 .068	.066 .067	.066 .069
C-52 to 55	G1	.078 .127	.066 .110	.048 .126	.046 .110	.051 .110	.057 .109	.091 .109	.093 .109	.082 .113	.093 .110	.091 .101				
	G2	.070 .173	.080 .216	.089 .118	.097 .101	.104 .110	.101 .114	.106 .119	.106 .113	.106 .125	.106 .115	.105 .108	.106 .108	.106 .108		
	G3	.110 .230	.153 .310	.155 .344	.167 .365	.320 .360										
	G4	.090 .131	.111 .130	.116 .140	.133 .154	.151 .155	.155 .190	.146 .170	.158 .190	.154 .187	.153 .203					
	G5	.037 .213	.039 .165	.040 .163	.058 .069											
	G6	.160 .170	.140 .180													
4340	G1	.060 .105	.082 .135	.097 .133	.105 .110	.112 .114	.114 .114	.112 .117	.114 .123	.124 .138	.139 .150					
C-43 to 45	G7	.059 .076	.096 .097	.083 .086	.078 .090	.102 .105	.098 .108	.110 .116	.114 .122	.124 .138	.137 .150					
17-7PH																
C-39 to 40	G1	.042 .110	.045 .123	.042 .126	.050 .127	.054 .130	.062 .126	.126 .130	.111 .118	.121 .135						
	G6	.040 .090	.072 .120	.087 .148												
	G8	.055 .178	.059 .083													
HY80																
C-18 to 20	G1	.102 .165	.144 .170	.155 .192												
	G2	.094 .108	.108 .148	.152 .161												
	G5	.213 .213														
	G6	.128 .162														

TABLE II. - MAXIMUM AND MINIMUM COEFFICIENTS OF FRICTION OF VARIOUS DRY FILM LUBRICANTS VS NORMAL UNIT LOAD

		NORMAL UNIT LOAD KSI														
BASE MT'L	LUB.	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
440C	UNBONDED															
	AL_2O_3 + MoS_2	.198 .220	.170 .310	.213 .350												
	$ZrSiO_2$ + MoS_2	.139 .190	.110 .110	.100 .100	.081 .102	.069 .093	.072 .086									
	D4	.101 .116	.102 .108	.087 .092	.069 .072	.059 .064	.053 .065									
	C-52 to55	.028 .034	.020 .021	.020 .034	.035 .067											
	RESIN BONDED															
	D5	.098 .110	.082 .090	.094 .097												
	D6	.210 .220														
	D7	.120 .15[illegible]	.090 .113	.100 .150	.085 .090	.071 .076	.067 .068	.064 .064	.068 .074	.074 .089	.141 .146					
	D10	.121 .160	.10[illegible] .139	.099 .119	.102 .147											
	D12	.118 .151	.099 .166	.088 .112	.083 .110	.076 .088	.074 .088	.069 .099	.066 .068	.061 .063	.057 .060	.055 .056	.051 .054	.049 .054	.054 .059	
	INORGANIC BONDED															
	D3	.087 .102	.054 .070	.050 .065	.048 .061	.045 .069	.047 .061	.050 .071	.045 .081	.048 .089	.047 .100	.046 .048	.046 .047	.047 .073		
	D8	.120 .124	.108 .114	.100 .102	.090 .090	.080 .080	.071 .074	.064 .064	.059 .060	.053 .056	.051 .051	.048 .048	.044 .044	.041 .041	.041 .041	.037 .037
	D11	.137 .148	.124 .148	.137 .137												
	MLF5	.086 .148	.084 .110	.074 .100	.070 .100	.068 .094	.051 .098	.063 .095	.060 .087	.058 .079	.056 .079	.052 .078	.050 .071	.046 .072	.047 .067	.045 .070
	MLF9	.074 .106	.050 .069	.044 .059	.044 .055	.042 .051	.039 .049	.036 .045	.032 .045	.031 .046	.029 .042	.029 .042	.029 .040	.028 .038	.025 .037	.025 .036
	SPECIAL															
	D1	.046 .053	.043 .052	.040 .055	.049 .101											
	D2	.074 .106	.058 .067	.061 .079												

TABLE II. - MAXIMUM AND MINIMUM COEFFICIENTS OF FRICTION OF VARIOUS DRY FILM LUBRICANTS VS NORMAL UNIT LOAD - concluded

		NORMAL UNIT LOAD KSI														
4340	INORGANIC BONDED	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
C-43 to 45	D3	.098 .105	.074 .076	.067 .072	.060 .068	.064 .067	.064 .066	.062 .064	.060 .060							
	MLF5	.070 .130	.062 .098	.060 .102	.053 .100	.050 .097	.043 .090	.033 .084	.037 .074	.043 .066	.043 .060					
	MLF8	.110 .125	.103 .105	.083 .087	.078 .081	.069 .073	.062 .067	.060 .062	.053 .055	.050 .053	.043 .048					
	MLF9	.027 .030	.045 .050	.041 .042	.036 .038	.032 .038	.032 .033	.027 .066	.027 .027							
17-7PH	INORGANIC BONDED															
C-39 to 40	MLF5	.121 .143	.093 .120	.085 .105	.074 .097	.074 .092	.072 .088	.077 .083	.077 .080	.065 .078	.061 .075					
HY80	INORGANIC BONDED															
C-18 to 20	D3	.110 .149	.089 .122	.070 .117	.104 .110	.088 .101	.088 .093	.082 .088	.07[illegible] .08[illegible]	.071 .071	.071 .071					
	MLF5	.118 .120	.092 .093	.081 .086	.080 .080	.071 .074	.067 .068	.062 .065	.05[illegible] .060	.056 .056	.053 .055					
	MLF8	.099 .102	.080 .088	.071 .075	.066 .070	.065 .065	.057 .063	.060 .065	.061 .061	.060 .061	.058 .060					
	MLF9	.065 .078	.058 .063	.054 .061	.049 .060	.043 .053	.046 .055	.043 .052	.039 .049	.047 .050						



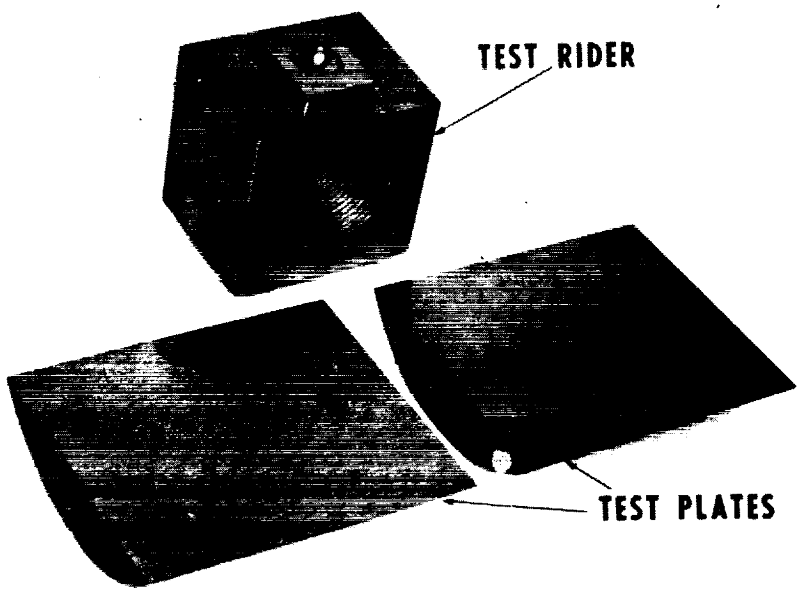


FIGURE 1. - TEST EQUIPMENT

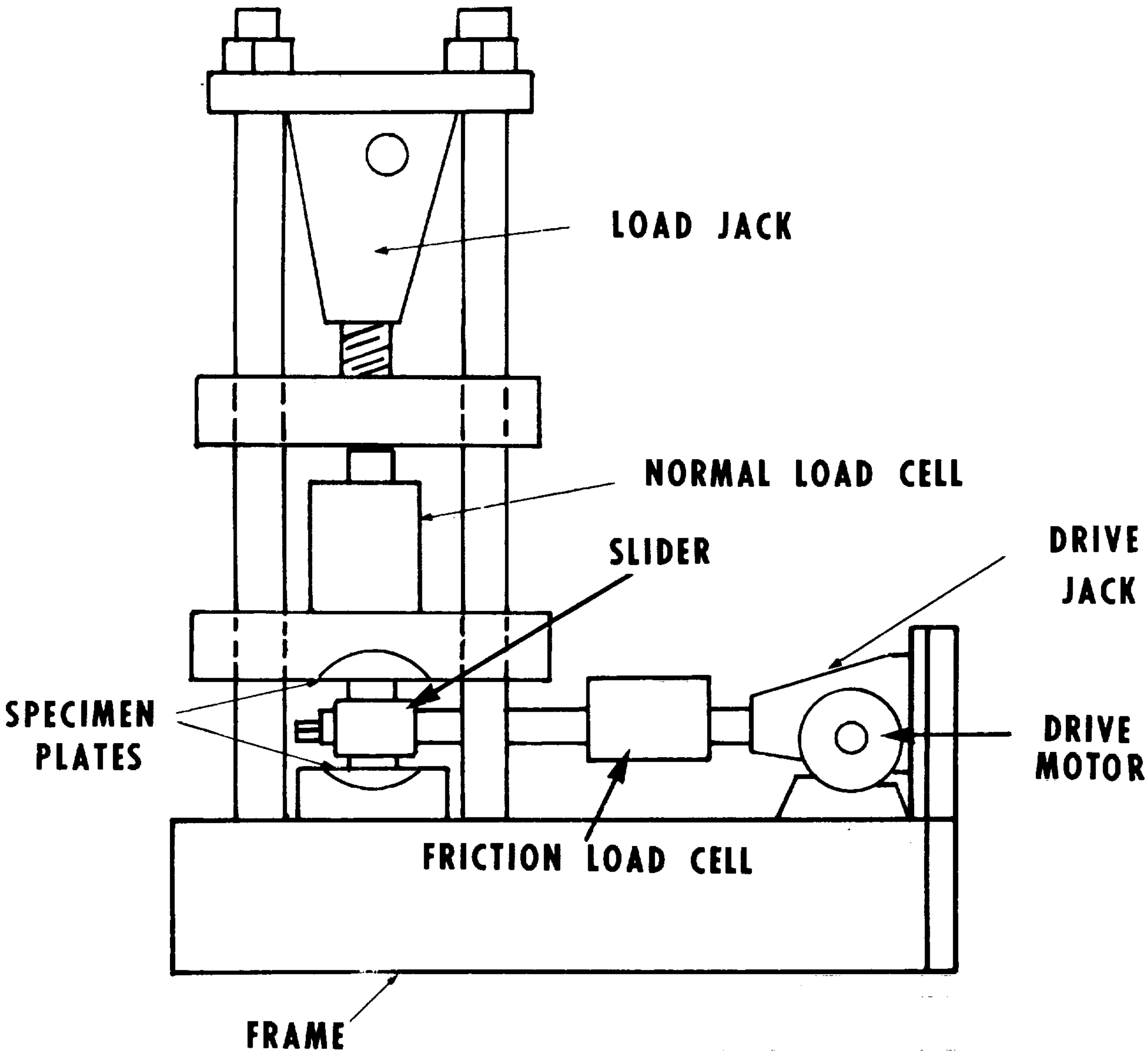


FIGURE 2. - SCHEMATIC OF HIGH LOAD TESTER

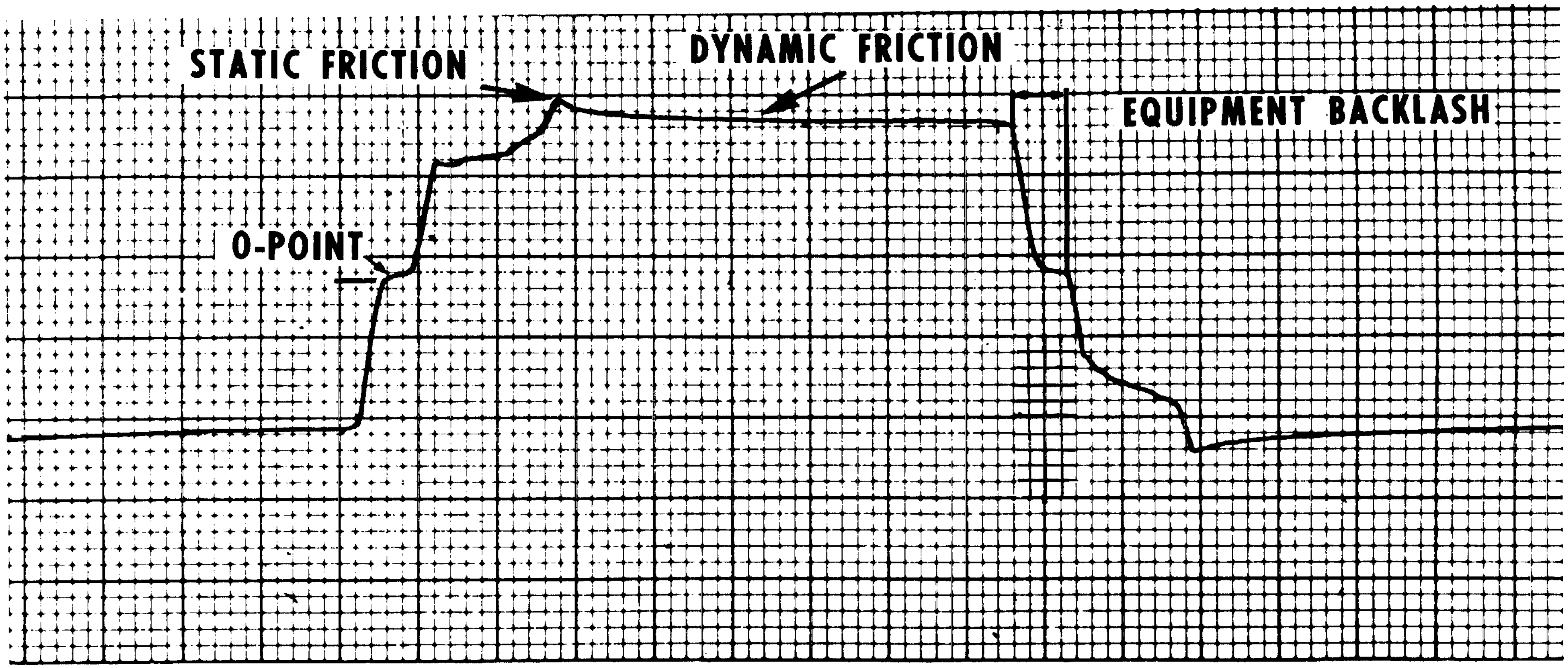


FIGURE 3. - FRICTION MEASUREMENT RECORDING

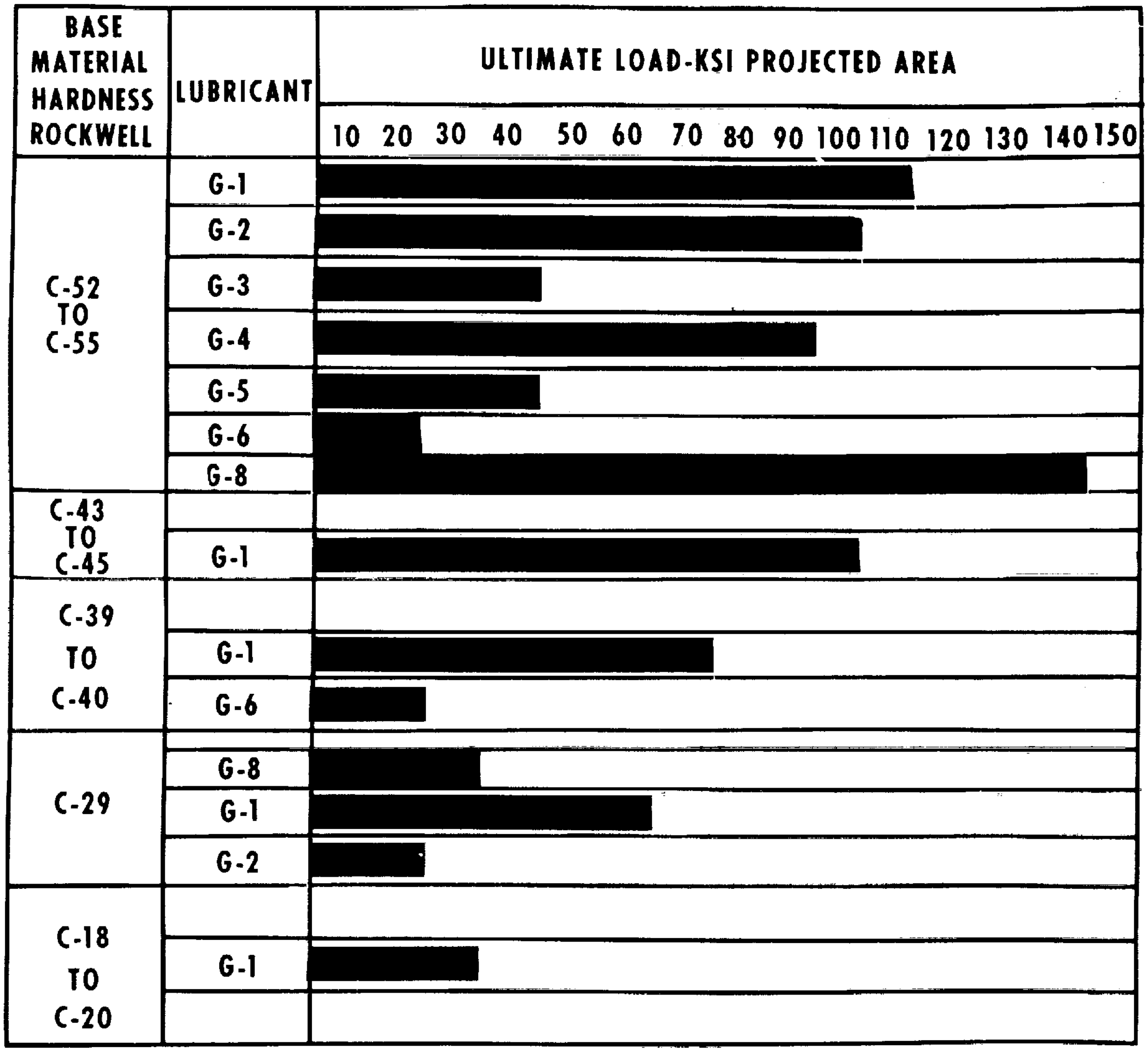


FIGURE 4. - GREASES, ULTIMATE LOAD CAPABILITIES WITH FOUR SUBSTRATE MATERIALS

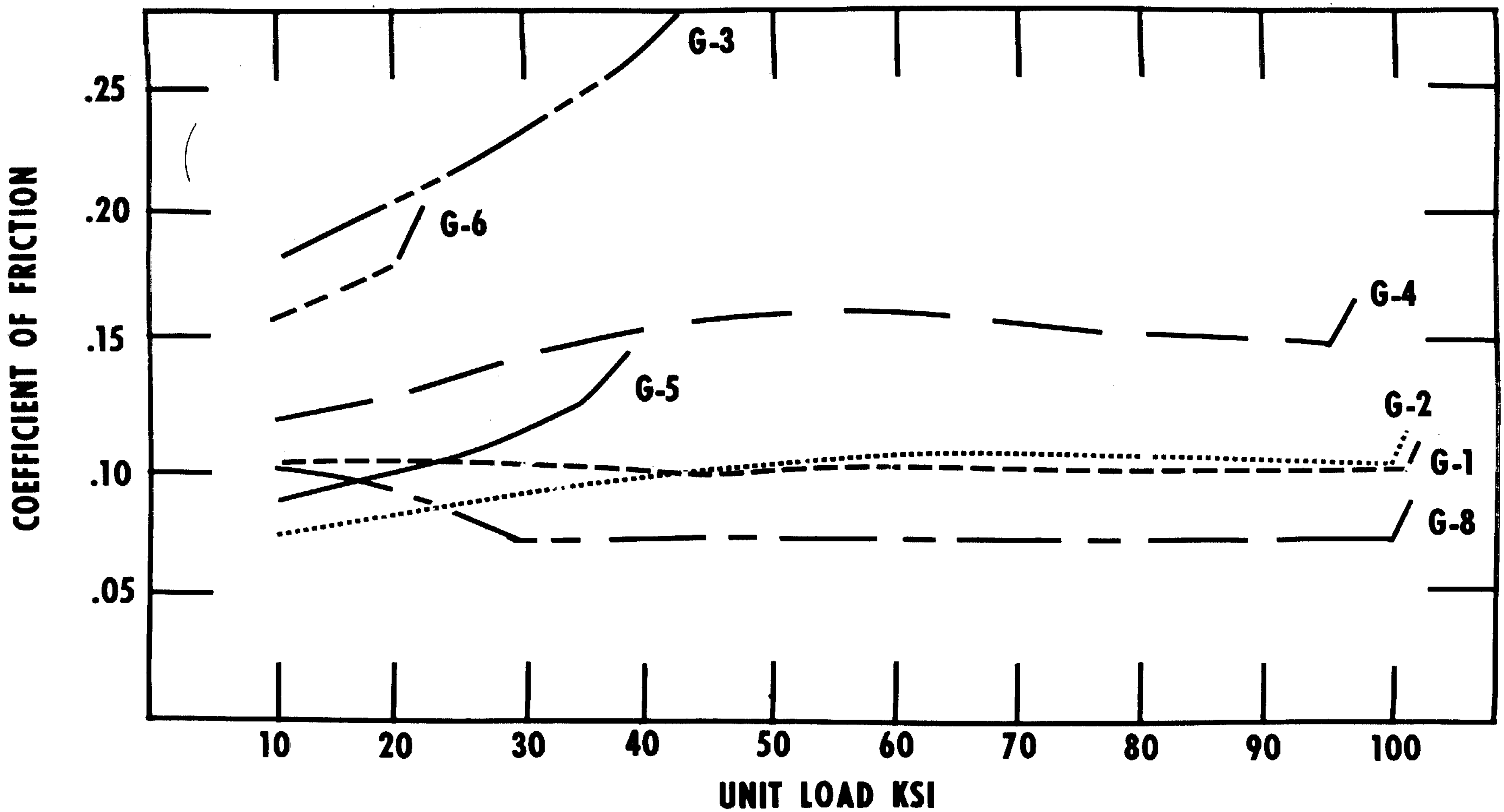


FIGURE 5. - GREASES, COEFFICIENT OF FRICTION VS UNIT LOAD FOR SEVEN LUBRICANTS, SUBSTRATE 440C ROCKWELL C 52-55

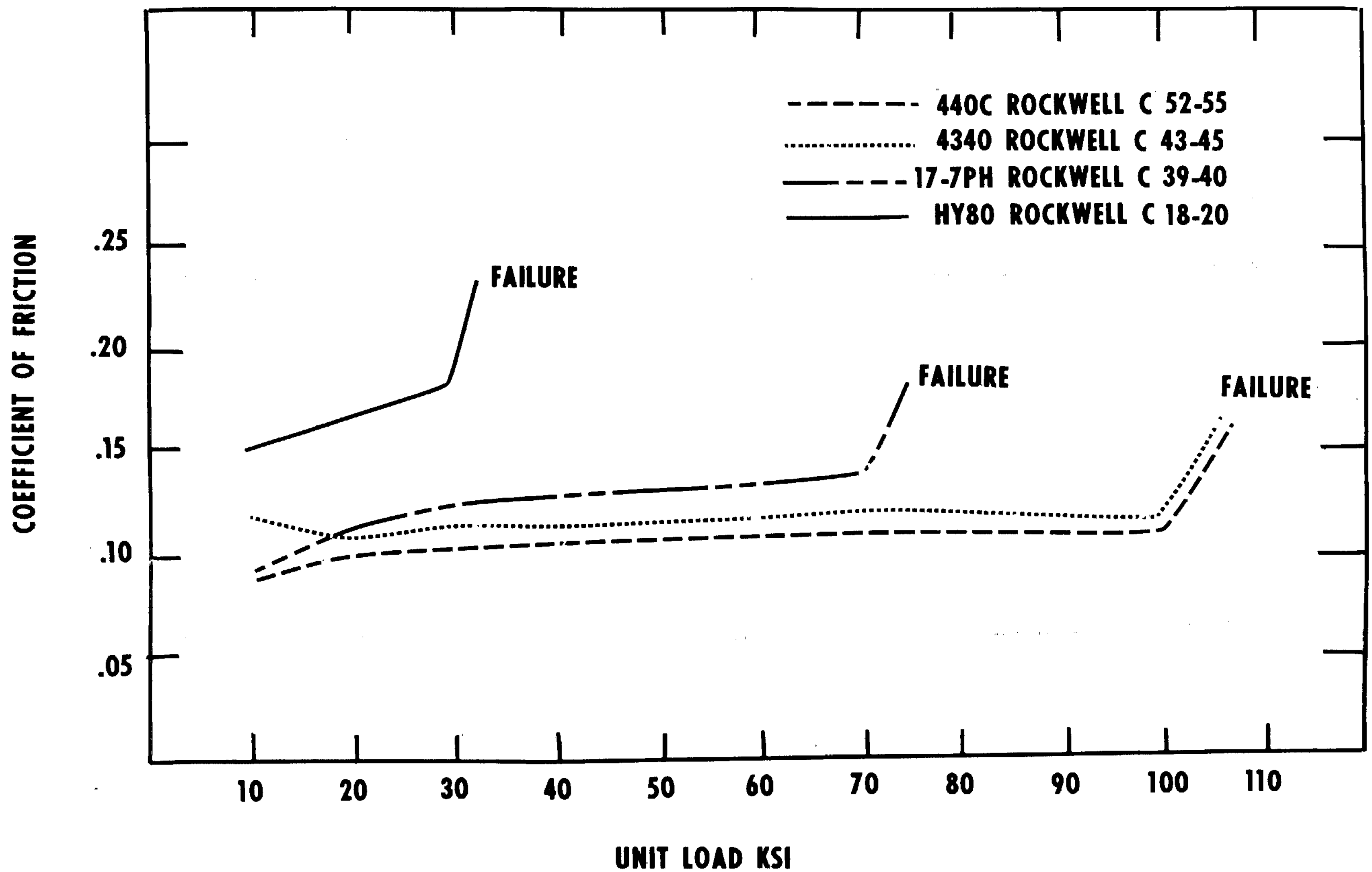


FIGURE 6. - COEFFICIENT OF FRICTION VS UNIT LOAD GREASE G-1
WITH FOUR SLIDER AND SUBSTRATE MATERIALS

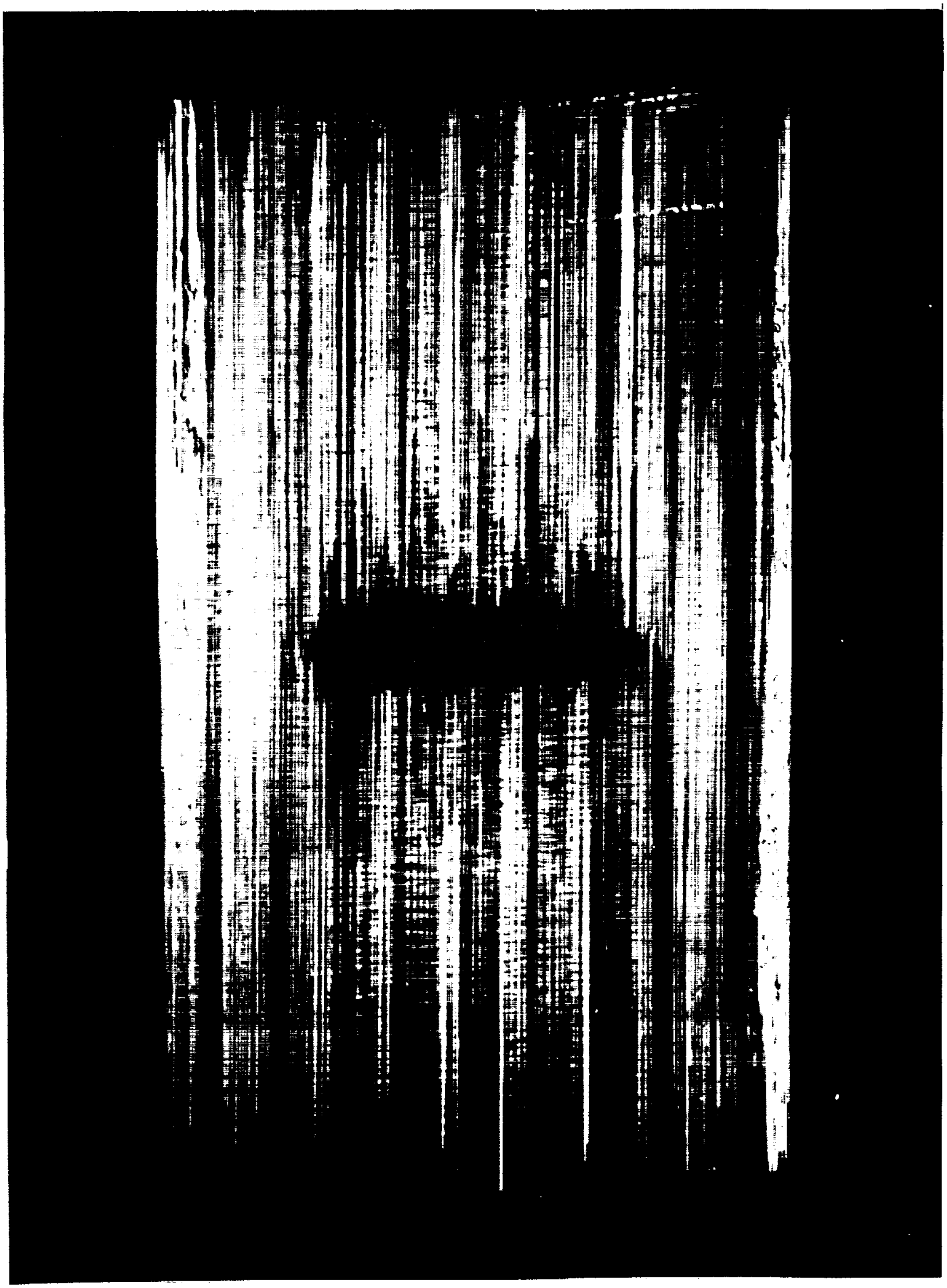


FIGURE 7. - GALLING ON 440C STEEL TEST PLATE LUBRICATED WITH GREASE G-1

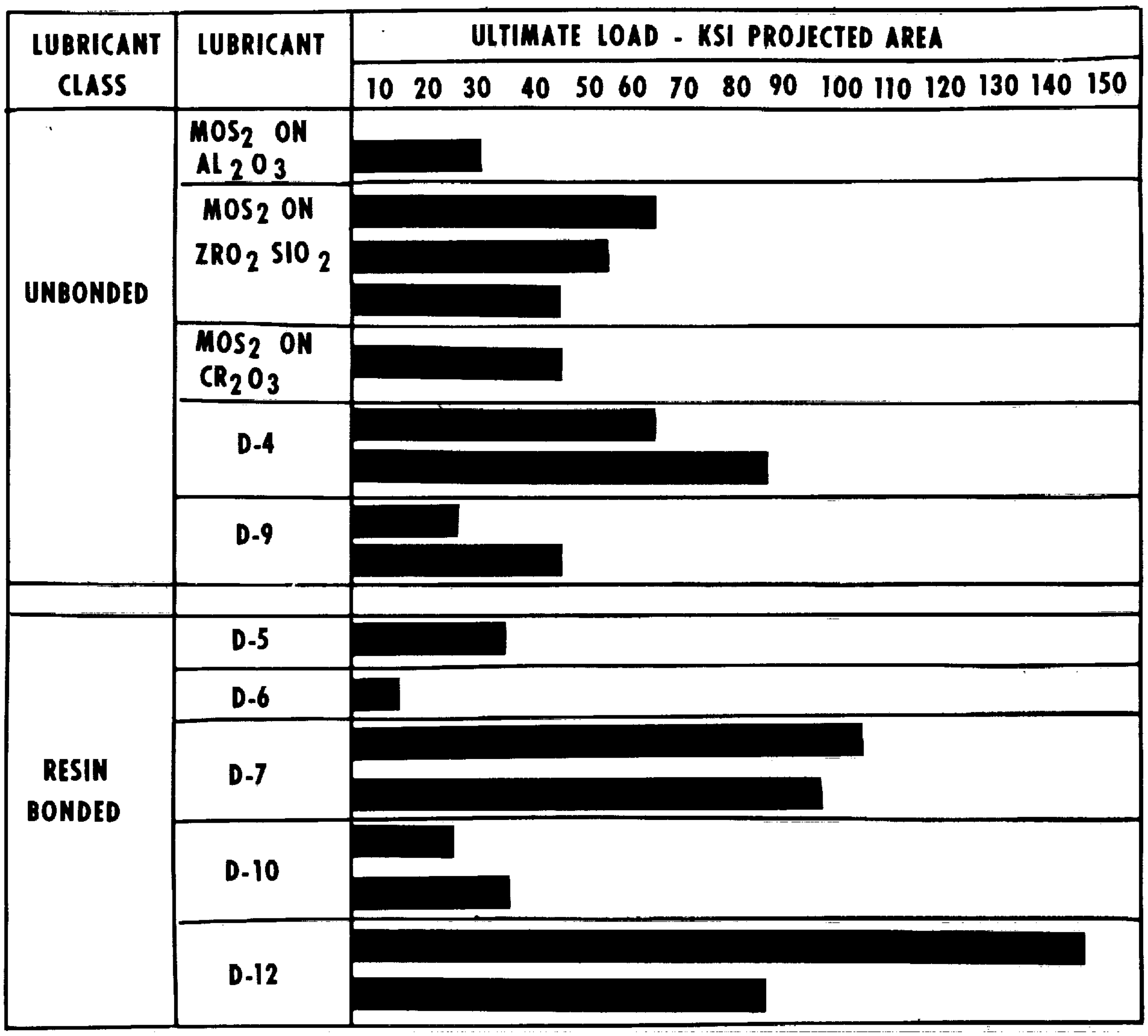


FIGURE 8. - DRY LUBRICANTS, ULTIMATE LOAD CAPABILITY FOR FOUR LUBRICANT CLASSES, SUBSTRATE MATERIAL 440C STEEL

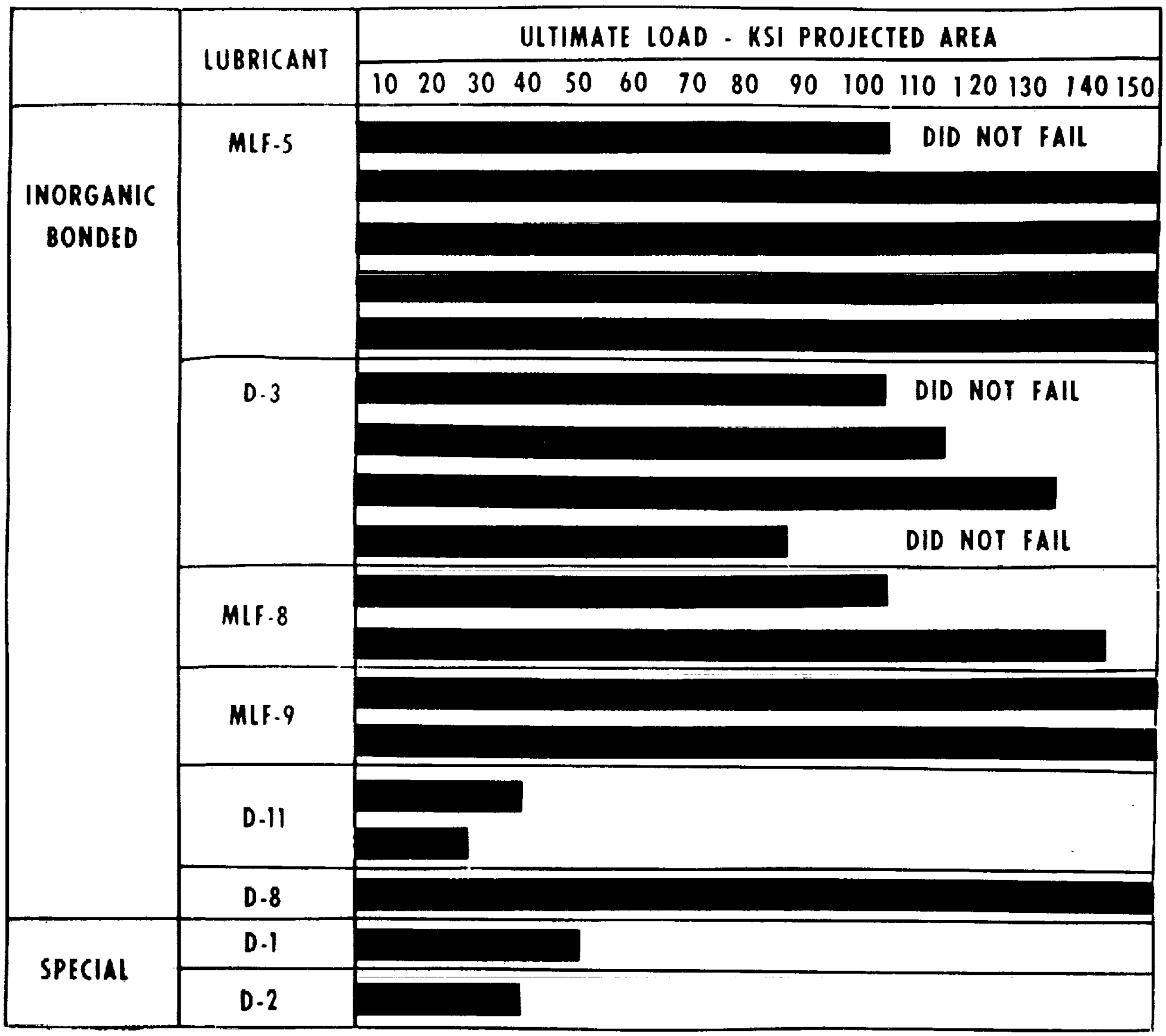


FIGURE 8. - DRY LUBRICANTS, ULTIMATE LOAD CAPABILITY FOR FOUR LUBRICANT CLASSES, SUBSTRATE MATERIAL 440C STEEL -concluded

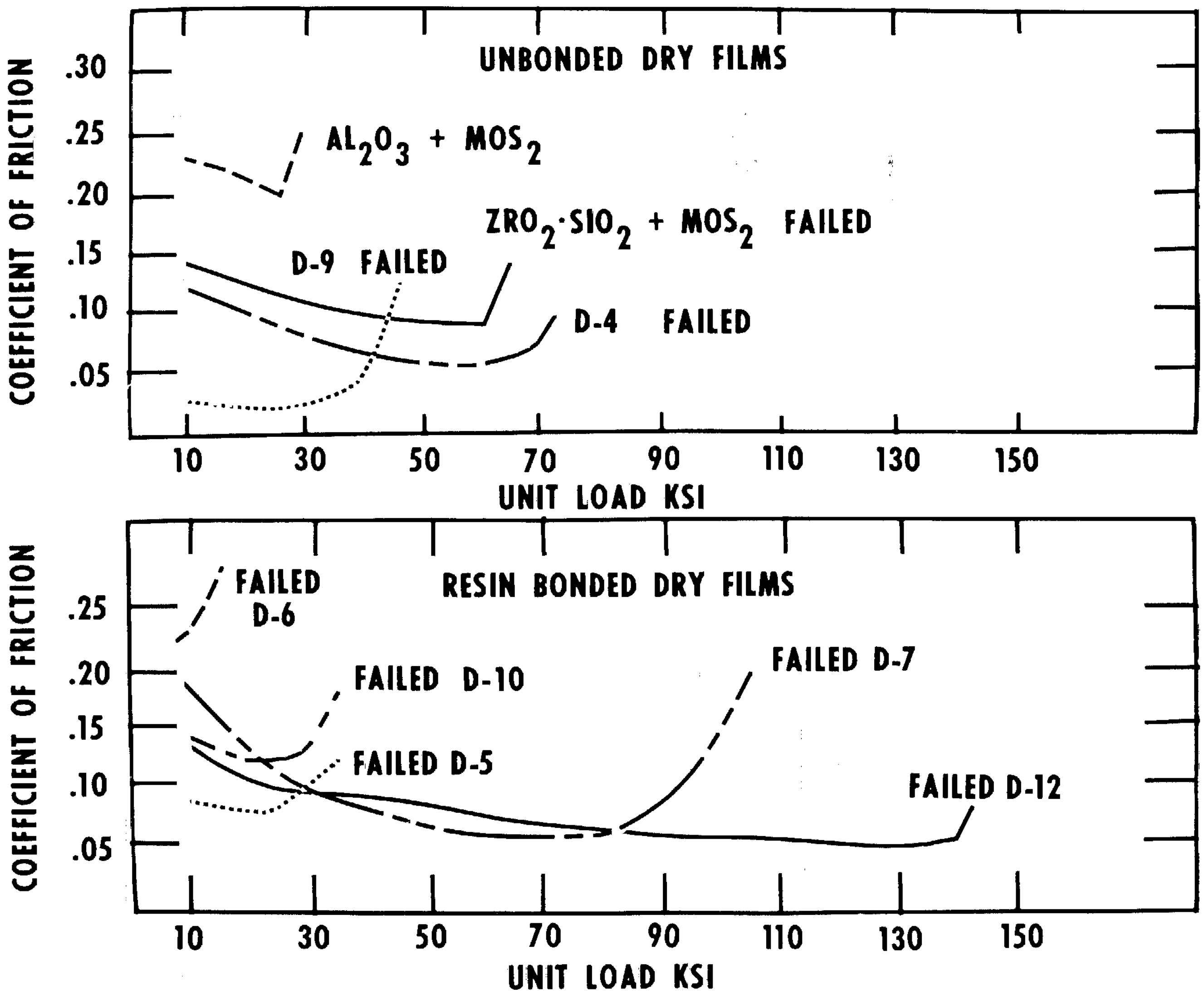


FIGURE 9. - FOUR CLASSES OF DRY LUBRICANTS, COEFFICIENT OF FRICTION VS UNIT LOAD SUBSTRATE 440C ROCKWELL C 52-55

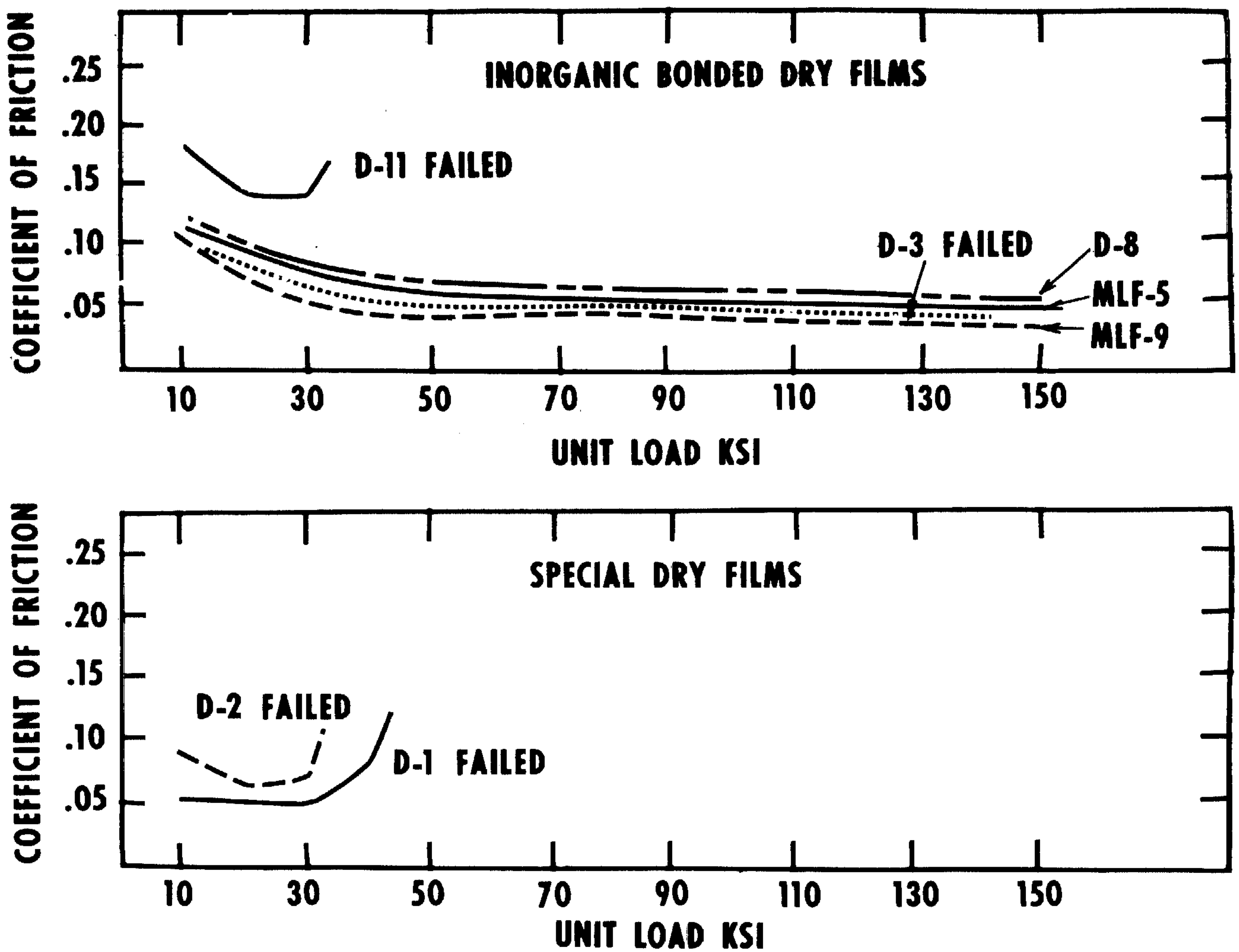
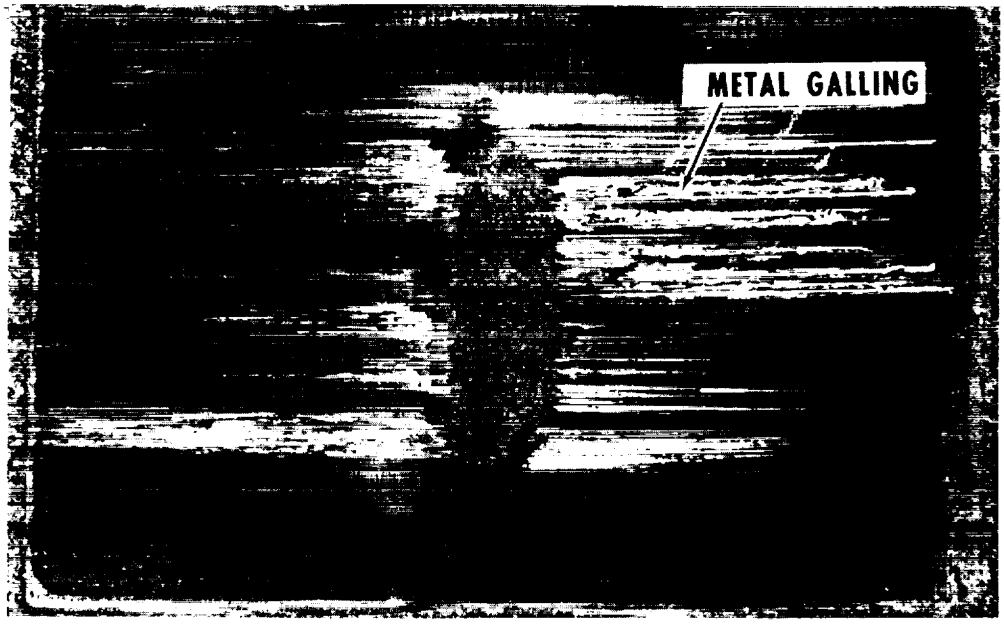
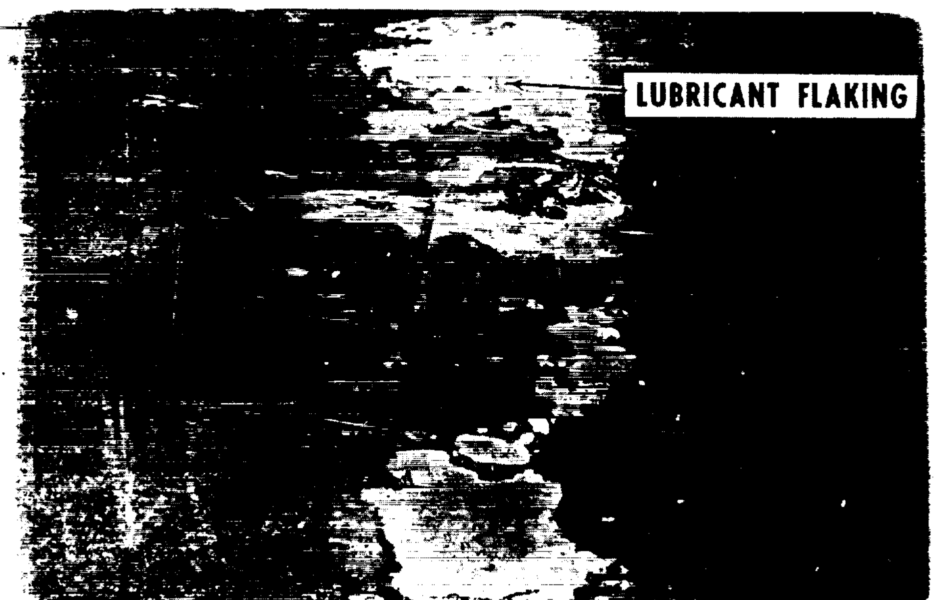


FIGURE 9. - FOUR CLASSES OF DRY LUBRICANTS, COEFFICIENT OF FRICTION VS UNIT LOAD SUBSTRATE 440C ROCKWELL C 52-55 - concluded



DRY LUBRICANT - GALLING AT 110,000 PSI



DRY LUBRICANT - NO GALLING TO 150,000 PSI

FIGURE 10. - TEST PLATES

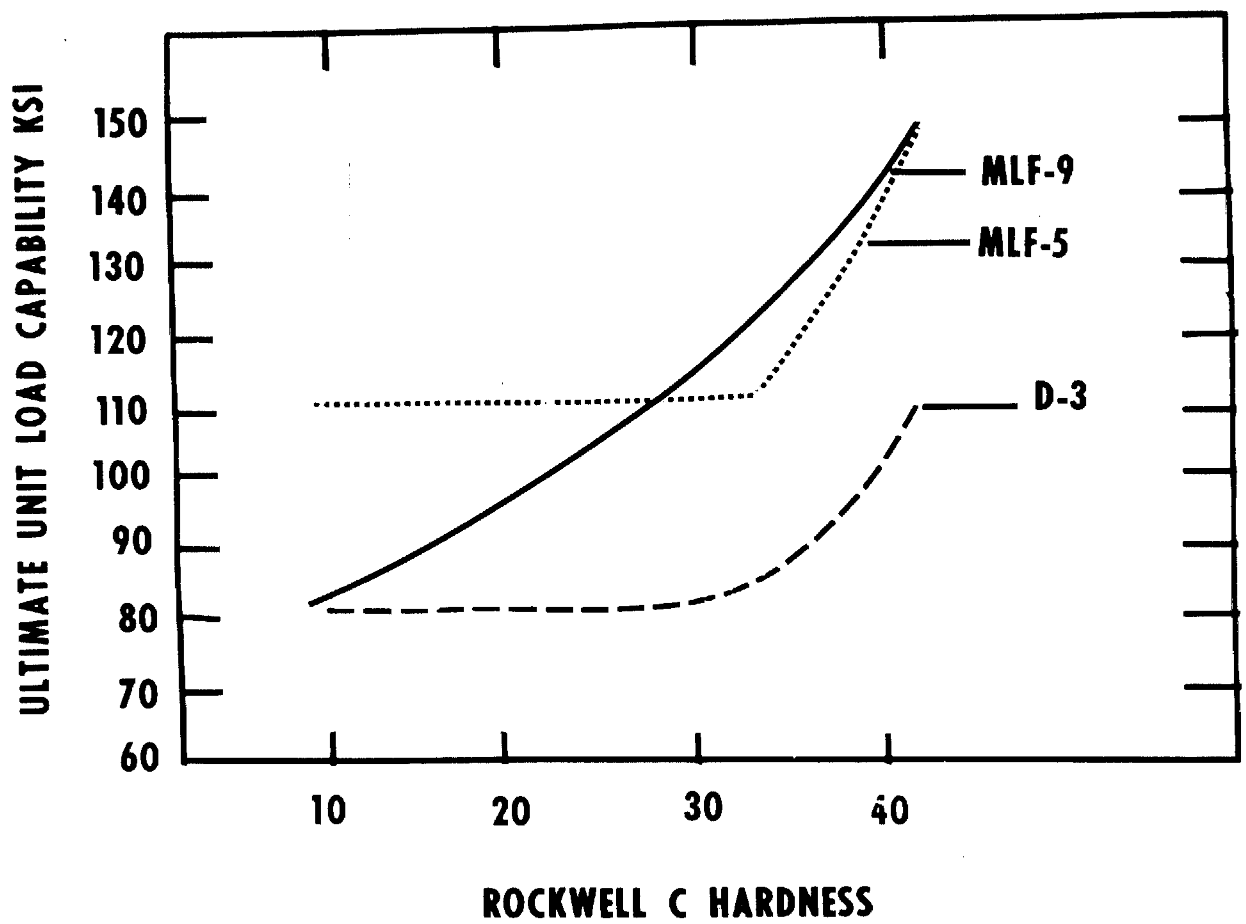


FIGURE 11. - DRY FILMS, ULTIMATE LOAD CAPABILITY VS SUBSTRATE HARDNESS

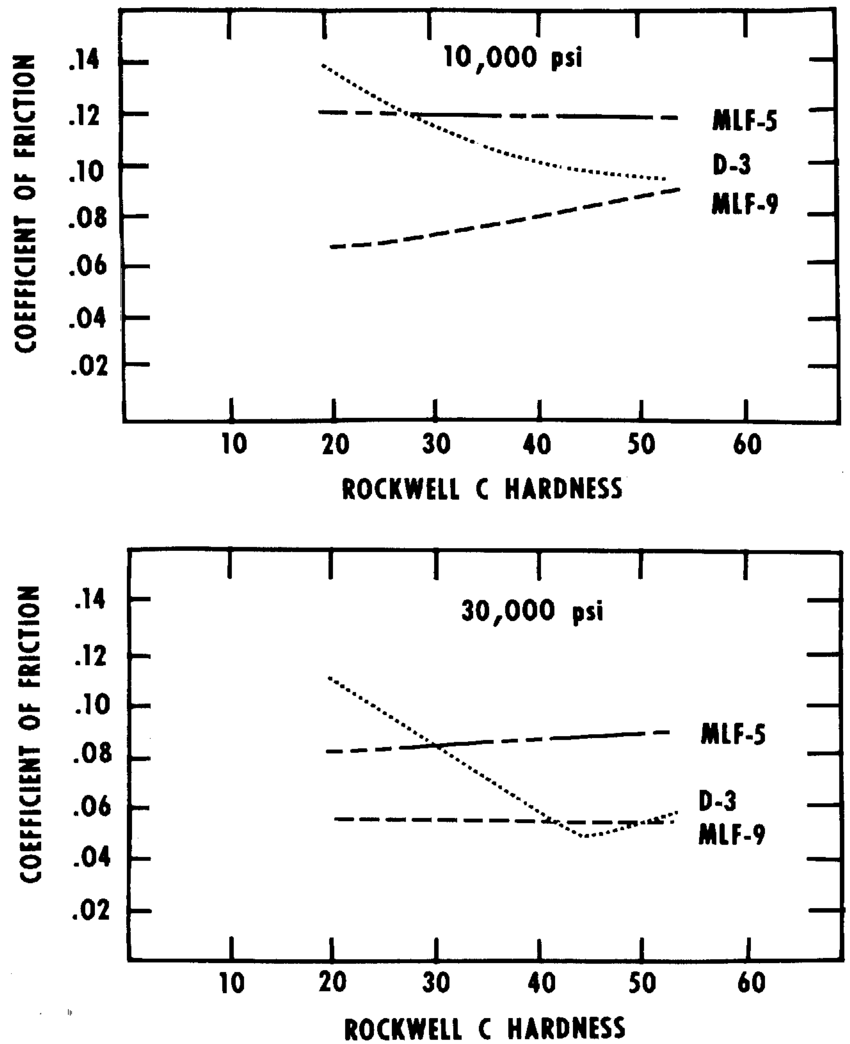


FIGURE 12. - DRY FILMS, AVERAGE COEFFICIENT OF FRICTION VS SUBSTRATE HARDNESS AT 10,000 PSI AND 30,000 PSI

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INVESTIGATION OF THE COEFFICIENT OF FRICTION OF VARIOUS GREASES AND DRY FILM LUBRICANTS AT ULTRA HIGH LOADS FOR THE SATURN HOLD DOWN ARMS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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